Journal of Industrial Intelligence
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Algorithmic Approach for the Confluence of Lean Methodology and Industry 4.0 Technologies: Challenges, Benefits, and Practical Applications

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Received: 05-10-2023 **Revised:** 06-18-2023 **Accepted:** 06-22-2023

Citation: D. Stojanović, J. Joković, I. Tomašević, B. Simeunović, and D. Slović, "Algorithmic approach for the confluence of lean methodology and Industry 4.0 technologies: Challenges, benefits, and practical applications," *J. Ind Intell.*, vol. 1, no. 2, pp. 125–135, 2023. https://doi.org/10.56578/jii010205.

Abstract: This study focuses on formulating an integration algorithm for manufacturing firms aiming to infuse the immense potential of Industry 4.0 technologies into lean manufacturing systems. The goal is to unlock and harness the advantages offered by these advanced technologies in an economically efficient manner. An analytic approach has been implemented in this investigation, examining a broad array of relevant empirical research. This comprehensive analysis serves to derive a universal algorithm predicated on the principles of both lean methodology and Industry 4.0. The complexities and challenges of amalgamating lean methodology and Industry 4.0 have been scrutinized meticulously in this study. The study elaborates on the extent to which Industry 4.0 technologies can augment lean production practices, delves into the difficulties encountered by corporations during the integration process, and suggests measures to surmount these obstacles. Moreover, potential benefits realized through this integration are explored. The algorithm proffered in this study permits a phased integration approach. Firms have the flexibility to adopt the integration in specific production segments or processes initially and progressively expand, aligning with their capabilities, resources, and the level of process maturity. Such an integration strategy allows companies to leverage Industry 4.0 in overcoming restrictions traditionally associated with the lean approach.

Keywords: Lean; Industry 4.0; Integration; Algorithm; Challenges

1 Introduction

Lean production embodies a paradigm that advocates for the development of supremely efficient processes, thereby contesting traditional manufacturing methodologies. It seeks to minimize non-value-adding tasks with the ultimate objective of providing high-quality products that prioritize customer satisfaction [1]. Yet, the burgeoning demand for a diverse range of highly customized products confronts the foundational principles of lean production. Originally tailored for mass production of similar products, lean production faces significant hurdles without the integration of sophisticated technology, such as that offered by Industry 4.0 [1]. Conversely, Industry 4.0 could potentially disrupt the lean production's core principle of simplicity and continual process enhancement [2].

Nonetheless, the incorporation of Industry 4.0 in production systems is conjectured to curtail complexity and render resultant processes more manageable [3]. Lean and Industry 4.0, while appearing divergent – with lean emphasizing people and processes, and Industry 4.0 focusing on advanced technologies – converge on the shared objective of enriching and propelling the production process across the entire value chain [4]. Both underscore the importance of process automation, albeit Industry 4.0 employs contemporary technologies to attain this goal [5].

According to Charrua-Santos et al. [6], although lean production presents a viable methodology for optimizing production, it necessitates the integration of cutting-edge technology and strategies to respond effectively to significant shifts in market demand. This study delves into the challenges, advantages, and potential drawbacks of amalgamating lean methodologies with Industry 4.0 principles. A conceptual algorithm is also proposed to facilitate this integration, aiming to harness the combined potential of these two powerful paradigms.

2 Lean Production

Lean embodies an enduring philosophy of growth that is primarily focused on creating value for customers, society, and the economy by curtailing costs, enhancing delivery time, and elevating quality via the elimination of waste [7, 8]. As a management system, lean is structured to cater to the needs of both employees and stakeholders, deriving its potency from foundational principles supported by straightforward processes and tools. The meticulous application of these principles has been observed to yield a plethora of benefits for organizations, including augmented quality of products and services, an increased market share, improved revenue, a heightened customer focus, and an expedited response to fluctuating market conditions [9].

In essence, lean promotes the accomplishment of superior outcomes with fewer resources. This includes the reduction of space, human effort, machinery, and materials, while concurrently striving to meet customer demands. The quintessential principles of lean, as delineated by Womack and Jones [10], are enumerated as follows:

• Value Definition: From the customers' perspective, value is construed as a product or service capable of fulfilling their needs at an acceptable price, and within the requisite timeframe.

• Value Stream Mapping: This principle encompasses mapping all activities germane to the production process. Through such mapping, companies can ascertain which activities contribute value directly, which are supportive, and which constitute losses warranting elimination.

• Flow Creation: Value-adding activities are organized and connected into a continuous flow to circumvent the creation of inventory, unplanned rework, or longer lead times.

• Pull Establishment: Conforming to the just-in-time principle, production is triggered only when necessary and in the required quantity. The production process should be customer order-driven.

• Continuous Improvement Implementation: Improvements should be encouraged and implemented across all operational levels within the organization.

Imai [11] delineated seven types of waste pervasive in every process:

• Overproduction: Production that exceeds demand.
• Waiting: The holding pattern of materials or resources for each other.
• Transportation: Redundant movement of materials in the transformation process.
• Over-processing: Exceeding quality characteristics that are not required.
• Motion: Redundant movement of people or equipment.
• Defects: Work related to creating, identifying, and correcting defects.
• Excess Inventory: Parts, unfinished production, and goods not in the process.

The literature also mentions the eighth type of waste, denoting situations where the full potential and talents of people and employees remain unexploited. Collectively, these categories contribute to a shared waste - the waste of time [11]. By identifying these sources of waste or losses, organizations can utilize lean tools for their elimination and continuous improvement. It should be ensured that each lean tool is applied in alignment with the predefined objectives sought to be achieved [1].

3 Industry 4.0

Industry 4.0 represents a paradigm aimed at the formation of intelligent factories through the convergence of physical operations and advanced technologies encompassing big data analytics, the Internet of Things, additive manufacturing, virtual reality, cloud computing, robotic systems, and cyber-physical systems [6]. From a technical perspective, Industry 4.0 is characterized by Kolla et al. [12] as the "digitalization of the production sector, characterized by embedded sensors in virtually all product components and production equipment, pervasive cyber-physical systems (CPS), and extensive data analysis." It results in the creation of a network that fuses the physical and virtual realms via cyber-physical systems [13].

From a production angle, it encompasses intelligent components that autonomously determine their own trajectories through the factory, with machinery capable of detecting these movements and communicating with the appropriate storage in real time. The information generated is predominantly employed for process evaluation and control, leading to highly flexible and self-regulating systems [14]. Industry 4.0 signifies technological progress wherein the internet and its related technologies interconnect physical entities, human actors, intelligent machines, production lines, and processes across organizational frontiers to engender a novel type of intelligent, networked, and agile value chain [15].

Wagner et al. [16] portray Industry 4.0 as an industrial vision that facilitates connections between individuals and objects at any time, any location, with anything and anyone, utilizing any network, path, or service. It should be highlighted that Industry 4.0 is not solely premised on technological possibilities but also encapsulates a managerial vision. The integration of management strategies into intelligent factories fosters the development of new business models and processes [16].

Mirroring lean production, Industry 4.0 is also predicated on a set of principles [17]:

• Compatibility: Smart factory systems engage in open and standardized network communication via the Internet of Things and the Internet of Services.

• Virtualization: By orchestrating cyber-physical systems (CPS) within smart factories, virtual simulation models are designed to facilitate data sharing and fault notification.

• Real-time Capability: Continuous monitoring and analysis of every element within the smart factory enable timely reactions to machinery failures and the rerouting of products to alternative apparatus.

• Decentralization: RFID tags, providing information on necessary manufacturing activities, empower computers within smart factories to permit cyber-physical systems to make autonomous decisions.

• Service Orientation: Cyber-physical systems and human actors are accessible through the Internet of Services, facilitating product-specific processes and customized manufacturing.

• Modularity: Smart systems are crafted to be flexible and adaptable to evolving requirements, permitting the substitution or augmentation of individual modules.

4 Results

4.1 Integration of Lean and Industry 4.0

Lean production, characterized by its pursuit of waste elimination and increased efficiency through the optimization of processes, presents an antithetical yet harmonious relationship with Industry 4.0. The latter emphasizes the digitization of the manufacturing process through advanced technologies such as the Internet of Things (IoT), big data, and artificial intelligence.

Although their foci differ, an interdependence and integration of lean principles and Industry 4.0 principles can be demonstrated, each contributing to heightened efficiency and productivity in manufacturing and business contexts. The employment of lean principles aids in the identification of production waste and inefficiencies, providing opportunities for rectification through Industry 4.0 technologies. Reciprocally, the real-time data and insights provided by Industry 4.0 technologies facilitate the optimization of lean processes, driving further waste reduction [17].

As depicted in Table 1, a matrix underscores the association between lean and Industry 4.0 principles through the application of Industry 4.0 technologies, with an 'X' signifying the existence of such connections.

Table 1. Connection between lean and Industry 4.0 principles [17]

Lean princples	**Industry 4.0 principles**					
	Interoperability	Virtualization	Decentralization	Real-Time Capability	Service Orientation	Modularity
Define Value	X			X	X	
Map Value Stream	X	X	X	X		
Create Flow	X	X	X	X	X	X
Establish Pull	X	X	X	X		X
Continuous Improvement	X	X	X	X		

Evidently, each lean principle is affiliated with a minimum of three Industry 4.0 principles, with flow creation being the sole lean principle linked to all Industry 4.0 principles.

Industry 4.0 technologies, including big data and analytics, are utilized to predict market demand and collate real-time customer data, with technologies such as RFID and cloud facilitating instantaneous customer contact. The dynamic data collected from big data analytics offers insights into the value stream map status at any given moment, and validates decentralized engineering decisions.

Cloud technology provides access to the value stream map for various actors, enhancing communication within smart factories and exemplifying the principle of compatibility. The cause of disruptions in the value stream often stems from processing activities, inventory counting errors, inadequate production capacity, and centralized control systems. Technological solutions such as real-time inventory status tracking help to circumvent inventory counting errors, while augmented reality technologies, including smart glasses and autonomous robots, minimize remodeling activities. This is consistent with the principle of virtualization.

The pull principle of lean manufacturing refers to a demand-driven production system where production is aligned with customer requirements in terms of quantity and timing. This principle is embodied in the kanban system, which can be augmented with real-time technology for self-organization. Technologies employed include big data analytics, which continuously monitors the production flow and integrates all sectors, RFID tags that log status and location, autonomous robots that receive instructions from cyber-physical systems (CPS) on resource replenishment timing and locations, and virtual simulations that perpetually update virtual maps based on supply chain data.

Smart facilities interconnected via cloud technology provide constantly updated data on production flow, equipment status, and potential failures. This information is collated by big data to identify decentralized improvement opportunities in the supply chain. Virtual simulations and augmented reality contribute to continuous process improvement by testing value stream optimization solutions on the virtual model before implementation, aligning with the principles of compatibility and virtualization.

The incorporation of lean production and Industry 4.0 technologies can create an influential synergy, driving significant improvements in efficiency, productivity, and quality. By assimilating these strategies, businesses can enhance agility and competitiveness while becoming more responsive to customer needs, thereby boosting profitability and growth.

The various 'lean' wastes can be addressed in the following ways by Industry 4.0 technologies:

• Overproduction: Real-time customer demand and inventory data facilitate optimized production schedules and prevent overproduction. Sensors on production equipment can detect idle machines and adjust production schedules accordingly.

• Waiting: Real-time data on equipment availability and production schedules helps reduce waiting times, ensuring resources are available when required and minimizing idle time.

• Transportation: Efficient transportation of materials and products is ensured by real-time data on inventory levels and production schedules, reducing unnecessary transportation.

• Excessive Processing: Real-time data on production performance and quality optimizes processing and reduces unnecessary processing steps.

• Movement: Unnecessary motion is minimized by real-time data on equipment performance and maintenance needs.

• Inventory: Unnecessary inventory is minimized by real-time data on inventory levels and demand.

• Defects: Real-time data on quality and production performance identifies and addresses issues before they become major problems, reducing defects.

• Unused talent: Efficient utilization of employees is ensured by real-time data on employee performance and availability.

The integration of lean and Industry 4.0 also has positive impacts on employee safety, as optimal workflow is achieved with efficient employees, less prone to errors and injuries [18]. This illustrates the contribution of Industry 4.0 technology to better waste elimination and efficiency.

Table 2 demonstrates the frequency of complementarity between Industry 4.0 technologies and lean tools.

Table 2. Combined Industry 4.0 technologies and lean tools, and combination frequency [19]

Lean and Industry 4.0 combination	Frequency
Utilization of real-time data to streamline continuous flow	65%
IoT infrastructure facilitating seamless integration and data interchange across shop-floor and additional departments	53%
Employment of CPS-based smart devices enabling operators to receive instantaneous error alerts	44%
Empowerment of human resources through mobile information for continuous enhancement, enabled by big data analytics	44%
Implementation of predictive algorithms enhancing autonomous maintenance	44%
Deployment of CPS to gather maintenance data and autonomously signal maintenance personnel, reinforcing TPM	38%
Application of Big Data technology improving VSM procedures	32%
Assistance from robots for workers performing standardized tasks	32%
Real-time data, supported by CPS, permitting automatic order processing and inventory level management via e-kanbans	32%
Utilization of advanced algorithms to enhance management of standard work procedures	27%

A system of ordering and replenishment inspired by the kanban method was introduced by the Wurth company. This system operates by deploying a sensor that detects the quantity of items in a storage basket, which then automatically transmits the data to a control system. An automatic ordering process to suppliers is thereby initiated, which results in inventory reduction and the liberation of storage space as orders are produced in line with demand.

At AGA Linda, a company that suffered from frequent welding errors attributed to insufficiently high temperatures required to merge two metal parts, a solution was found using Internet of Things technology. By installing smart sensors in welding guns, welders were informed when the temperature dipped below the acceptable range. Consequently, instant feedback allowed even inexperienced welders to halt the welding process and rectify temperature issues, thereby supporting the zero-defect principle of lean methodology. The subsequent reduction in superfluous activities, such as the refinishing or reworking of defective parts, led to a marked decrease in weld quality problems, reported to be between 20 to 50 percent, while also producing time and financial savings [20].

In the case of Magna, a car manufacturing company, the use of barcodes was extensively implemented to eradicate human errors and manufacturing mistakes. This was executed by having all operators log into their workstations via the scanning of barcodes attached to their wrists. Consequently, a record was created detailing which operator assembled which part [21]. Simultaneously, electronic work instructions were exhibited as visual aids at each workstation to guide operators in correctly assembling parts in the correct sequence within the production process. It was necessary for operators to continually adhere to the instructions displayed on the screen to circumvent errors, and to verify the correct torque values using sensors [21].

These examples demonstrate the conclusion that the application of Industry 4.0 principles can enhance the effectiveness of lean implementation.

4.2 Barriers to the Integration of Lean and Industry 4.0

Despite the apparent synergies between Lean and Industry 4.0, various obstacles can preclude manufacturing companies from reaping the full benefits of such an integration. In certain instances, lean tools alone cannot ameliorate these difficulties, necessitating the intervention of Industry 4.0 technology. Table 3 elucidates how specific tools and technologies may be leveraged to tackle distinct production challenges [3].

Table 3. Compilation of challenges mitigated by lean and/or Industry 4.0 [3]

Challenges within the production	Possible solution regarding lean management methods	Possible solution regarding Industry 4.0 technologies
Overproduction	Pull	CPPS
Missing standards	5 S	-
Central production controll	Pull	-
Material flow	Pull	CPPS, Smart product
Vast processes	Kanban, Genchi genbutsu/ go to gemba shopfloor visualization	CPPS Digital Kanban, Real-time visualization
Process errors	Poka Yoke	Assistance systems.Augmented Reality
Deficient products	Jidoka	-
Volatile customer demand	Heijunka	CPPS
Machine failure	-	Assistance systems, Augmented Reality
Worker absence	-	Assistance systems
Worker failure	-	Assistance systems, Augmented Reality
Volatile supply chain	-	CPPS
Scenario Planning	-	Simulation, Virtual Reality
Data consistency	-	OPC Standard, Digitization
Product tracing and tracking	-	CPS, QR-Codes, —NFC
Data collection	-	BDE/MDE, Big Data

One intriguing observation from Table 3 is that, rather than offering an Industry 4.0 solution, the lack of standards is addressed solely through the 5S tool. The plausible interpretation for this is the inherent potency of the 5S methodology, particularly the final stage - "Sustain", in mitigating standard-deficit scenarios. In such contexts, the infusion of technology within the 5S construct can buttress, or even necessitate, the preservation of self-discipline, thereby curbing any shortfall in discipline.

Challenges surfacing during lean implementation and their corresponding solutions via Industry 4.0 technology are outlined in Table 4 [22].

Table 4 manifests that a wide array of challenges can be addressed through the application of particular Industry 4.0 technologies. These findings were corroborated by experts during the interviews conducted by Schumacher et al. [15]. The most prominent obstacles they highlighted during the integration of Industry 4.0 technology into lean manufacturing practices include:

• An inadequate comprehension of the convoluted concept of Industry 4.0 and insufficient strategic guidelines for its assimilation, particularly in the context of lean production systems.

• A vague understanding of Industry 4.0, leading to uncertainties about its utility and the potential consequences, advantages, and associated costs of fusing Industry 4.0 technology with lean manufacturing practices.

• An inability to assess their competency for adopting Industry 4.0 technology and integrating it with the lean approach, which often induces reluctance and a refusal to take coordinated action.

Table 4. Encountered challenges during lean implementation and corresponding solutions offered by Industry 4.0 [22]

Dimensions of lean manufacturing	Challenges for lean implementation from integration perspective	Solutions provided by Industry 4.0
Supplier feedback	Limited expertise and resources	Collaborative manufacturing
	Difference in business models, operation and data maintenance practices	Better communication mechanisms
		Synchronisation of data
JT delivery by suppliers	Incomplete goods' shipping status	Item tagging
	Mismatch in quantity of transported goods	Wireless tracking of goods
	Unexpected delays during transportation	Smart reallocation of order
Supplier development	Inadequate resources and expertise	Standardised interfaces
	Equipment compatibility between organisations	Virtual organisations - synergetic cooperation
Customer involvement	Little flexibility for product alteration	Elongated freeze period
	Relationship between needs and functions	Large volume QFD
	Acquiring exact customer needs	Usage analysis
Pull production	Improper track of supplied material quantity	Material replenishment monitoring
	Changes in production schedule	Schedule tracking and kanban updating
Continuous flow	Errors in inventory counting	Real-time inventory tracking
	Capacity shortages	Subcontracting
	Centralized control systems	Decentralized decision making
Setup time reduction	Human experience-based process adaptation	Self-optimization & machine learning
		Workpiece-machine communication
Total productive/ preventive maintenance	No control of machine breakdown	Machine-worker communication
	Unknown problem solving time	Self-maintenance assessment
		Predictive maintenance control system
Statistical process control	Ignorance of operators	Workpiece-machine communication
	Inability to track process variations	Improved man-machine interface
		Process tracking, integration & management
Employee involvement	Improper feedback mechanisms	Smart feedback devices
	Performance evaluation practices	Worker support systems
	Monotony in work	Improved man-machine interface

These challenges were similarly identified by Akdil et al. [23] in their research and were considered significant barriers to commencing integration. Once a certain degree of integration between lean production and Industry 4.0 is accomplished, novel obstacles may arise. Smart factories often grapple with issues related to inexperienced and transient staff members who lack proficiency with large IT and hardware projects, web technology, programming, and related methods [24]. Continuous challenges include real-time data availability, inadequate standardization, decentralized data collection, constrained movement data, data security issues, and the formidable task of ensuring complete interconnectivity of factory systems per Industry 4.0 principles within supply chains [25].

Typically, larger organizations possess an edge in effectively deploying the lean approach. Charrua-Santos et al. [6] attribute the limited success of small and medium-sized enterprises (SMEs) in lean implementation to factors such as the misuse of lean production tools, an insufficient understanding of Lean due to a lack of management commitment to lean philosophy, decision-making weaknesses arising from incomplete lean tool implementation, and an absence of support from external consultants, government entities, and suppliers. Therefore, it would be intriguing to explore whether the integration of lean production and Industry 4.0 is advisable and profitable solely for large enterprises.

4.3 Rigorous Evaluation of Lean and Industry 4.0 Integration

The IDC report, as referenced by Wielki and Koziol [26], estimated a spend of nearly $2.7 trillion on information technology solutions by companies in 2020. An annual growth rate of 4.7% was projected for the demand for IT services within manufacturing and financial institutions, surging to $475 billion in 2020. The high investment necessity in Industry 4.0 technology implementation becomes evident when lean production alone falls short of generating substantial savings and adequately fulfilling market demands [5]. Focusing solely on cost reduction, the Boston Consulting Group estimated that individual application of lean principles and Industry 4.0 technology could result in a cost reduction of 15% to 20% and 10% to 15%, respectively. However, the integration of both could potentially lead to cost reductions exceeding 40% [27]. Consultancy firm Brian and Company underscored the financial merits of Lean 4.0, positing that factories could realize savings of 30% and expedite payback periods compared to traditional lean's typical 15% reduction in operating costs [18].

With a potential efficiency improvement and cost savings exceeding 40%, the integration of lean methodologies and Industry 4.0 offers a lucrative prospect for manufacturing companies [28]. Thus, it can be inferred that such integration yields significant financial benefits and positively impacts an organization's key performance indicators (KPIs).

Lean methodologies aim to eliminate waste, with digital technologies accelerating this process and reducing the reliance on human intervention [18]. Thus, introducing Industry 4.0 technology within lean manufacturing companies can amplify the effectiveness of lean principles [29]. Regardless of Industry 4.0 support, efficient processes are paramount for successful business operations; Industry 4.0 cannot replace lean methodologies in any aspect [28]. Lean forms the bedrock for successful production, and Industry 4.0 technology facilitates its application optimization [30]. Merely recognizing the potential of applying Industry 4.0 is insufficient for manufacturing companies; successful integration into their operations is crucial [20]. This fact holds for any Industry 4.0 technology. Bauer et al. [30] proposed an integration framework for Industry 4.0 and lean manufacturing, as depicted in Figure 1.

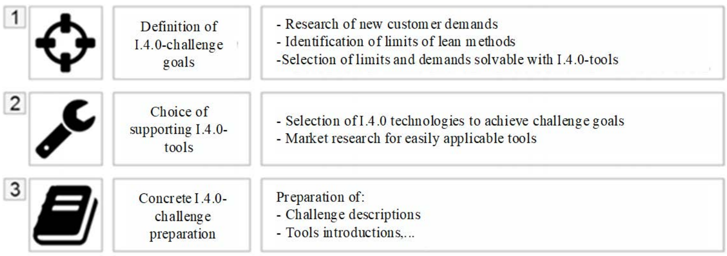

Figure 1. Lean production and Industry 4.0 integration [30]

This proposed framework initiates by examining customer needs and identifying challenges not sufficiently addressed by lean methodologies alone. It then involves selecting the appropriate technology to mitigate these challenges and researching best practices for its implementation [30]. After establishing the actions and methods, an action plan is created to address the issue, followed by the introduction of Industry 4.0 technology [30]. It is noteworthy that some companies may allocate considerable resources and effort to automate their existing production processes, often neglecting the critical step of optimizing these processes prior to automation [31].

Figure 2 illustrates the methodological flow of integrating lean methodologies and Industry 4.0 [32].

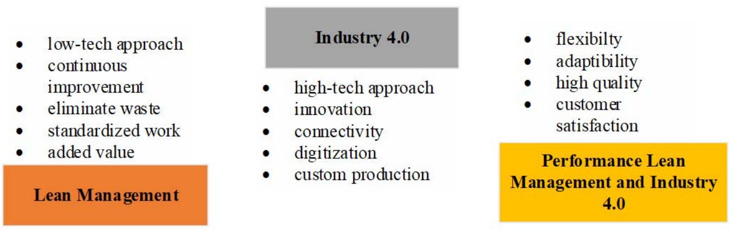

Figure 2. Methodological flow for lean management-Industry 4.0 integration [32]

Both approaches aim to enhance productivity by optimizing and rationalizing production processes. Their integration in an industrial environment can amplify customer satisfaction through the delivery of high-quality products and services tailored to their needs. Additionally, it meets the productivity prerequisites of adaptability and flexibility in production, necessary to deliver products and services that align with dynamic customer demands [32].

In conclusion, the integration of lean methodologies and Industry 4.0 presents significant potential. This integration is justified from several standpoints, and the complementary nature of lean production and Industry 4.0 in terms of their objectives is apparent.

5 The Algorithm for the Integration of Industry 4.0 into Lean Implementation

Tissir et al. [1] posited that the automation of inefficient processes would only intensify and consolidate their inefficiency. Given that most initiatives implementing Industry 4.0 could potentially fail without being contextualized within the fundamental principles of production management [33], the importance of process optimization and organization based on lean principles before integrating Industry 4.0 into production is emphasized. Subsequently, Industry 4.0 should be utilized to rectify the limitations, deficiencies, risks, and unused capacities unaddressed by lean methodologies. It is underlined by Rossini et al. [33] that Industry 4.0 may find smoother implementation at company echelons where lean practices are already well-integrated into the factory.

Figure 3 presents a proposed algorithm to guide companies in integrating Industry 4.0 into their lean production endeavors. The algorithm is designed to facilitate partial integration within certain segments of production or processes, incrementally progressing based on capacities, resources, and maturity level.

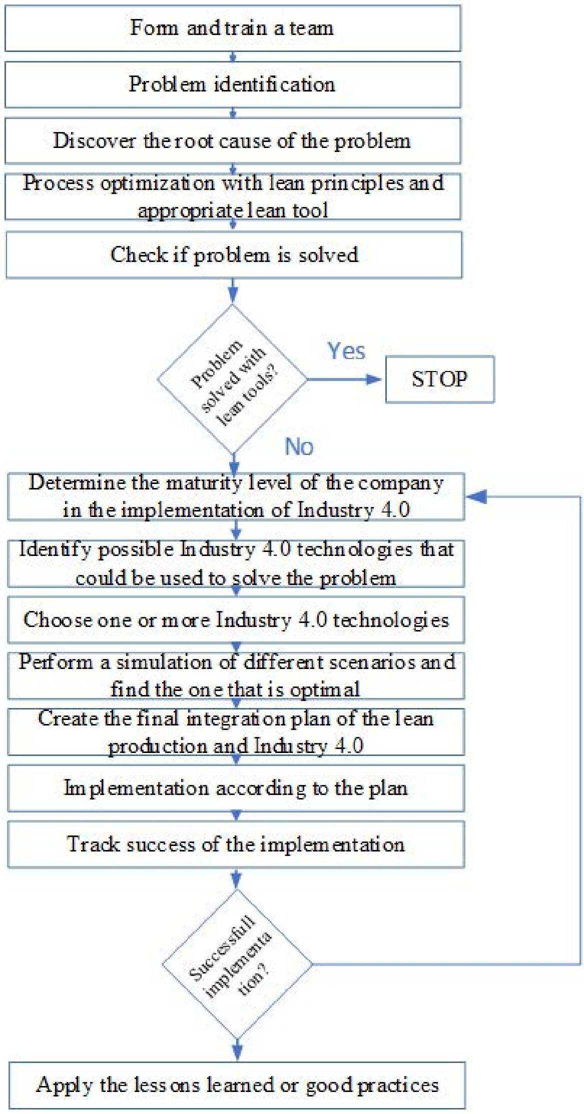

Figure 3. Proposed algorithm for the integration of Industry 4.0 into lean implementation

The algorithm initiates with the formation and training of a dedicated team for the integration of lean production and Industry 4.0. A problem is then chosen and prioritized using methods like a Pareto diagram. The problem's root cause is identified, followed by the assessment of whether the process aligns with lean principles, and whether an existing lean tool can solve the problem or optimize the process effectively. In case lean principles are not presently applied, the process should be optimized using an appropriate lean tool. Subsequently, an evaluation is conducted to ascertain whether the application of the lean tool has fully resolved the issue. If it has, the improvement process ceases, and there is no requirement to introduce Industry 4.0 technology. However, if the issue persists, the company's maturity level in implementing Industry 4.0 must be assessed as a prerequisite for the subsequent step.

Based on literature reviews, best practices, and the company's maturity level, potential Industry 4.0 technologies capable of addressing the problem are listed. A selection is made from one or more of these technologies to be applied, based on factors such as budget, estimated profitability, and the company's capacities and capabilities.

Simulating different scenarios helps identify the optimal solution. A final integration plan for lean production and Industry 4.0, hinging on the chosen technology, is then developed. The implementation of this plan is tracked, and in case of failure, the company's maturity level in implementing Industry 4.0 should be reassessed and the algorithm continued accordingly. In the event of successful implementation, lessons learned, and good practices should be applied throughout the production process as necessary and feasible.

Though this algorithm provides a high-level framework for integrating lean production and Industry 4.0, further research is essential to provide specificity to certain steps. It is applicable to both small-to-medium enterprises and larger corporations. However, the specific implementation of each step might vary based on the unique circumstances and requirements of each company.

6 Conclusions

The central theme of this study was the exploration of the integration between Industry 4.0 and lean production practices, with a focus on identifying the challenges encountered during integration, understanding potential benefits, and proposing an algorithm for facilitating integration. The necessity for integrating the lean approach and Industry 4.0 has been substantiated from various angles, demonstrating significant similarities and complementarity in terms of objectives.

Key advantages of integration include:

• Establishing a connection between the lean principles and the principles of Industry 4.0, which can be facilitated through the application of Industry 4.0 technology.

• Utilizing Industry 4.0 technology as a mechanism for eliminating all eight types of production losses.

• Improving responsiveness to market demands.

• Simultaneously enhancing the flexibility and automation of production through the integration of the lean approach and Industry 4.0.

• Overcoming challenges that are insurmountable solely by the application of the lean approach.

• In certain contexts, facilitating the partial introduction of Industry 4.0 technology into production, targeting specific parts or processes, without the need to establish the appropriate structure throughout the entire factory at once.

• Facilitating inter-organizational connections along the supply chain that also apply Industry 4.0 technology.

However, the integration process presents certain disadvantages:

• Integration can prove to be costly and time-intensive.

• The development of an integration strategy necessitates a thorough understanding of the context of integrating lean production and Industry 4.0.

• Successful integration is unattainable without prior optimization of processes, thus requiring additional time.

For future research, an algorithm to prioritize the integration of the lean approach and Industry 4.0 is suggested for consideration, enabling organizations to more effectively determine the starting point for integration.

It was observed that each lean principle can be associated with at least three Industry 4.0 principles, with flow creation being the singular lean principle linked to all Industry 4.0 principles. The role of Industry 4.0 in eliminating eight types of production losses was examined, highlighting that no type of waste cannot be improved by the application of some of the Industry 4.0 technologies. Certain Industry 4.0 technologies were found to be effective in eliminating various categories of losses, while certain types of losses could be addressed by the application of multiple different Industry 4.0 technologies.

Industry 4.0 technologies offer a solution to challenges that lean tools alone cannot address. In relation to the challenges encountered during the implementation of lean production or the limitations of lean production, it was noted that no such challenge is beyond resolution through the application of some of the Industry 4.0 technologies. Challenges such as changing and inexperienced staff, and the availability of real-time data, were identified. Ultimately, a prerequisite was established: before the integration of Industry 4.0 into lean production efforts, optimization of what is to be automated must first be conducted.

The proposed universal integration algorithm could enable companies to address business problems in the most rapid, efficient, and profitable manner possible, even if the integration is only partial, focusing on specific segments of production or processes, and progressively implemented in alignment with current capacities, resources, and maturity level.

This study has extensively demonstrated that the integration of Industry 4.0 into lean production is not only necessary but financially justified, with significant impact on KPIs, and that these approaches are complementary. As a prerequisite, companies must understand the benefits, the disadvantages to be eliminated, the specifics associated with integration, and the level of effort required for the integration to yield the desired results before embarking on integration. This type of integration can leverage Industry 4.0 to eliminate limitations associated with applying the lean approach.

Data Availability

Not applicable.

Conflicts of Interest

The authors declare no conflict of interest.

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